The Drake Equation

f_c
N
f_p
f_l
f_i
L
R_*
n_e

SETI INSTITUTE

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The Allen Telescope Array. Credit: Simon Steel.

The Very Large Array radio telescope in New Mexico. The VLA is now being used by SETI Institute scientists to answer the question: *Are we Alone?* Credit: Bettymaya Footh, NRAO/AUI/NSF.

What is the Drake Equation?

How many alien civilizations could be out there in our Milky Way galaxy? How could we answer this question scientifically? What conditions are needed to make planets, life and intelligent beings who can build machines to communicate across the stars? We (humans) can, thanks to a long-lived star, a planet with lots of water, and billions of years of a good climate that allowed life to evolve. Maybe these conditions and our story have happened millions of times on millions of other planets. Or maybe we're unique. The Drake Equation helps us explore one of the greatest scientific questions: Are we alone?

The Drake Equation is a real scientific Equation. You can plug in numbers and get an answer (maybe you'll get "42"). Try it. But more importantly, the Equation is like a roadmap. It guides scientists through the galaxy, showing what's important, what discoveries we need to make, and what questions we should ask about the stars, planets and life.

$N = R_* f_p n_e f_l f_i f_c L$

Frank Drake and the Drake Equation Credit: Seth Shostak/SETI Institute.

The Drake Equation has many parts and needs different numbers to work. It might look harder than Einstein's $E=Mc^2$, but Frank Drake asks a more complex question. So, let's look at the Drake Equation and explore its parts. By the end, we will have learned about the galaxy, stars and planets, oceans, brains, language, war and technology. It is the story of life in the universe. It is our story.

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

Here’s what these terms mean:

$N =$

The number of communicating alien civilizations in our galaxy right now. We know at least “1” because that’s us, humans on planet Earth. We can send and receive messages between the stars.

R_*

How many stars are made in our galaxy every year.

f_p

The fraction of those stars that have planets.

n_e

The number of planets around each of those stars that could support life.

f_l

The fraction of those planets where life starts.

f_i

The fraction of those planets where intelligent life appears.

f_c

The fraction of those planets where intelligent life can communicate across the stars.

L

The typical number of years that a civilization can communicate.

Over the years, people have suggested new terms and different versions of the Equation, and that’s ok. The Drake Equation is a scientific thought experiment. It’s about the journey of discovery, which is good because the final answer might still be far away!

R

Westerlund 2 is a stellar nursery, with up to 3000 newborn stars. More stars are being born in the cocoon of gas and dust in the lower right of the image. Credit: NASA, ESA, Antonella Nota (ESA, STScI), Hubble Heritage Project (STScI, AURA), Westerlund 2 Science Team.

The stars as viewed from Aktau, Altyn Emel National Park, Kazakhstan, Earth. Credit: bbsferrari via Envato Elements.

R_* The rate of star formation in our galaxy

Take a look around you. The atoms that make up trees and rocks, the air we breathe, even the DNA that make up us. All were cooked in cosmic ovens we call stars. Even the Sun, our very own star, was born in the nuclear kitchen of an older, earlier stellar generation that exploded and spread the raw materials of planets and life throughout the galaxy. It's like Carl Sagan said, "We are all made of star stuff." It seems then that a natural first step in our journey is the birth of stars.

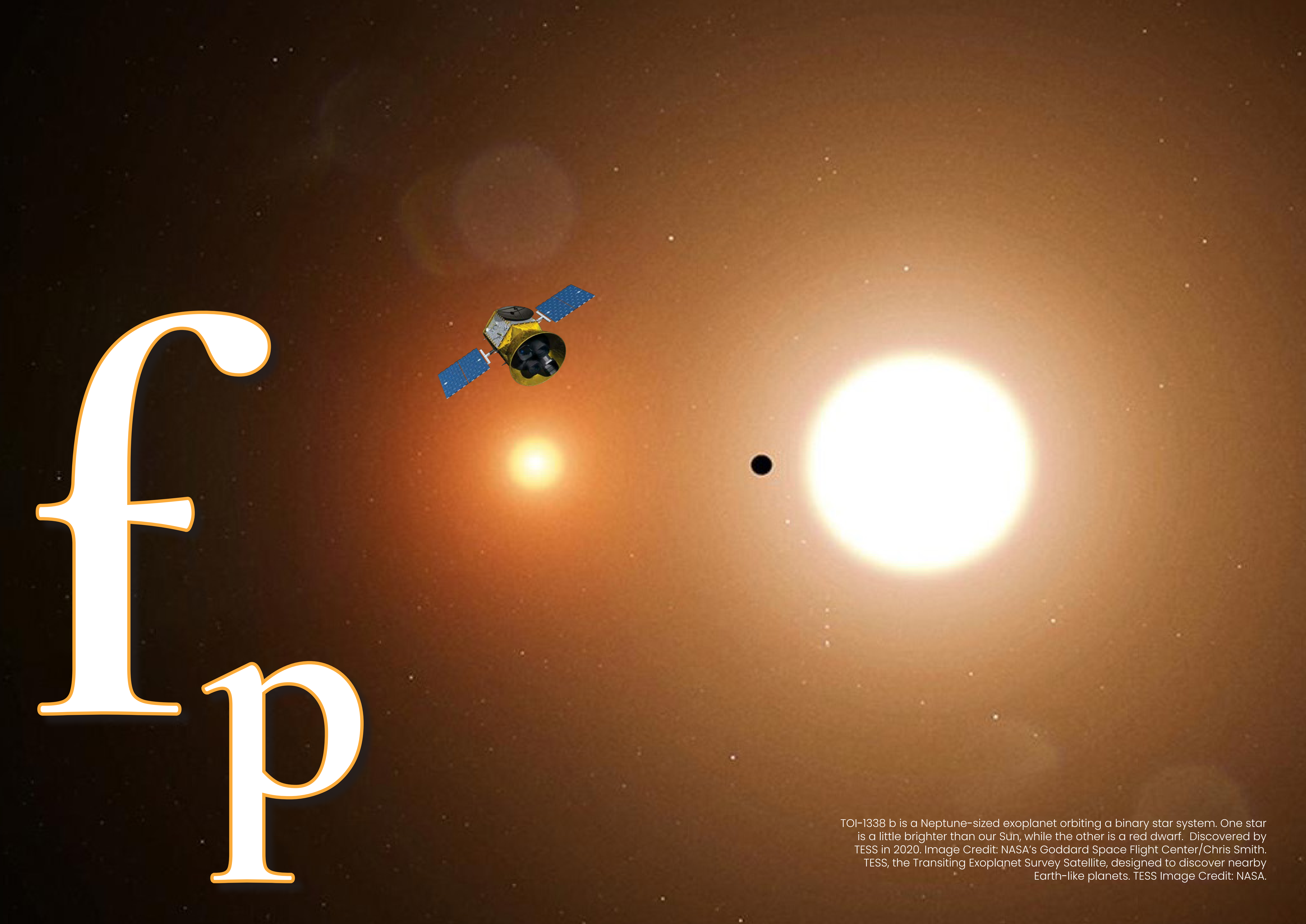
The Sun, and every star visible in the night sky, live in a city of stars that we call the Milky Way. Three hundred billion stars in a spinning pinwheel 100,000 light years across.

The Milky Way is like a cosmic factory, always making new stars. These stars are born from giant clouds of gas and dust. When old stars run out of fuel and die, they explode, spreading out new elements into space. These elements, along with hydrogen and helium, eventually clump together to form new stars. It's a never-ending cycle.

Since we're made of the same stuff as stars, the more stars the Milky Way makes, the more building blocks for life there are.

Astronomers have been studying star formation in the Milky Way for a long time. Using powerful telescopes like Hubble and JWST to measure the amount of gas and dust turning into stars each year, we can estimate that roughly 7 new stars are born in our galaxy each year. That may not sound like much, but the Milky Way has been in the star-making business for billions of years!

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$



f_p

TOI-1338 b is a Neptune-sized exoplanet orbiting a binary star system. One star is a little brighter than our Sun, while the other is a red dwarf. Discovered by TESS in 2020. Image Credit: NASA's Goddard Space Flight Center/Chris Smith. TESS, the Transiting Exoplanet Survey Satellite, designed to discover nearby Earth-like planets. TESS Image Credit: NASA.

Illustration of a planet. Credit: andreiuc88 via Envato Elements.

f_p The fraction of those stars that have planets

The cosmic city we call the Milky Way is home to about 300 billion stars, including our Sun. How many of our stellar neighbors have planets orbiting around them? Turns out, probably most of them. We didn't know this for a long time because planets are really small and stars are very far apart. Even our biggest planet, Jupiter, is tiny compared to the Sun. So, it was hard for us to see planets around other stars.

The first planet around another star was found in 1995. But we really started finding a lot more planets thanks to a space telescope called Kepler. Kepler could see when a planet passed in front of its star, making the star look a little dimmer.

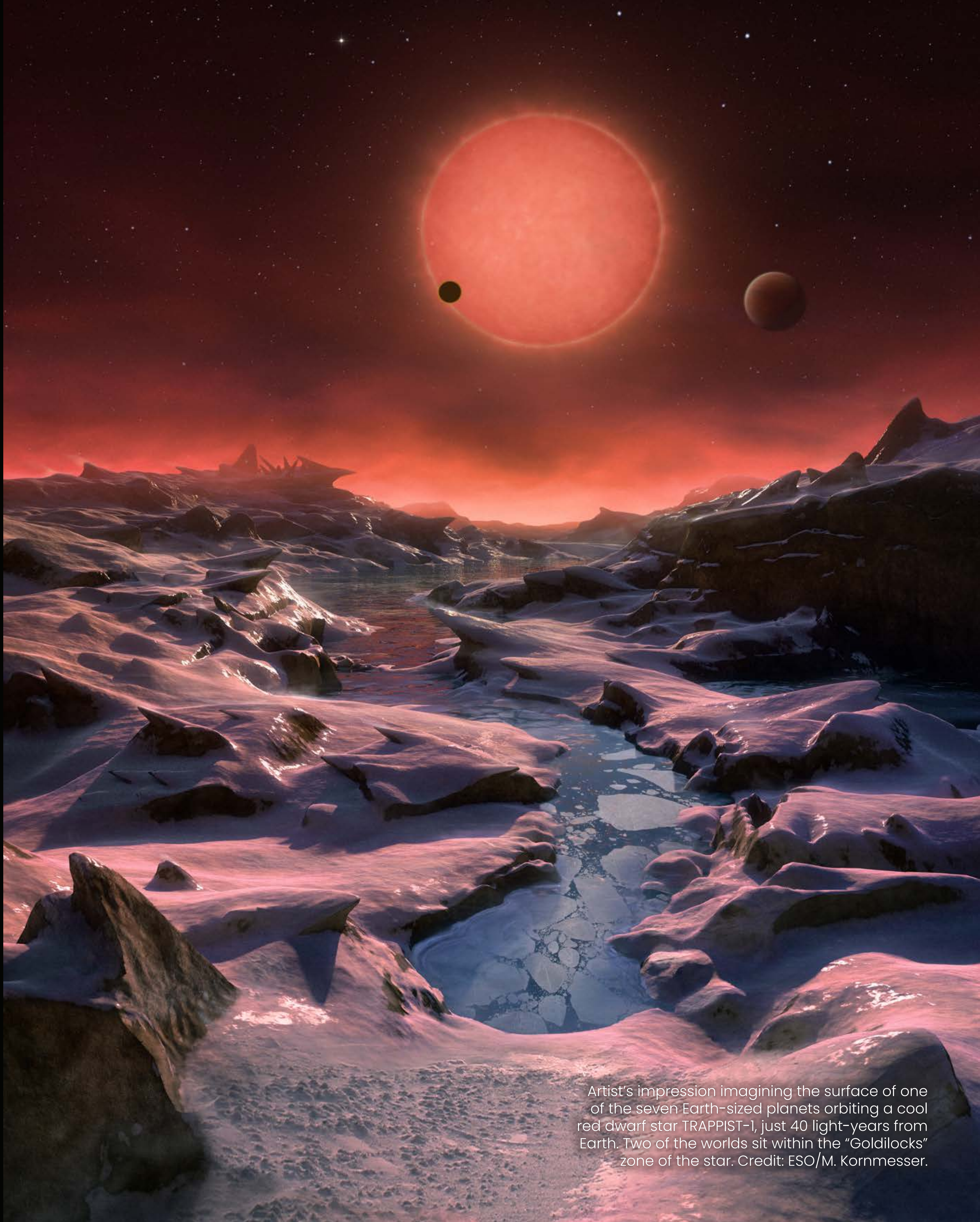
Because of Kepler and other telescopes, we've found thousands of planets which we now call extra-solar planets or "exoplanets." Some exoplanets are bigger than Jupiter, while others are about the size of Earth. We've even found planets orbiting binary stars!

Even though we've found *thousands* of planets, there are *billions* of stars. We've only found planets around stars that are close to us, and mostly planets that are easy to find. If we think about all the stars out there, and all the different kinds of planets that might exist, it's likely that most stars have planets, and we can set the value of f_p close to "1".

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

Jupiter’s moon Europa, showing its cracked icy surface that covers a warm liquid ocean. Photographed by the Juno spacecraft in 2022. Image Credit: NASA/JPL-Caltech/ SwRI/MSSS/Kevin M. Gill

ne



Artist’s impression imagining the surface of one of the seven Earth-sized planets orbiting a cool red dwarf star TRAPPIST-1, just 40 light-years from Earth. Two of the worlds sit within the “Goldilocks” zone of the star. Credit: ESO/M. Kornmesser.

3D render animation of an Earth-like planet made with media from NASA space images. Credit: NASA & goinyk via Envato Elements.

n_e The number of planets around each of these stars that are capable of supporting life

What makes a planet the right planet for life? Sometimes this term of the Drake Equation talks about worlds that are 'Earth-like." But we have to be careful. The planet Venus is almost Earth's twin, but its soupy carbon dioxide atmosphere and metal-melting temperatures means it's *probably* the last place you'd want to look! Unfortunately, even with our biggest telescopes, we are still a long way from telling whether an exoplanet is an Earth 2.0 or Venus 2.0.

What does Earth have that Venus doesn't? The answer is liquid water. A liquid allows molecules to move around, mix and combine to build up the complex molecules that form the basis of life. Without a liquid, molecules are frozen in place, or are boiled away. But there are other ways to generate the heat needed to keep water wet. Jupiter is a long way outside the Goldilocks Zone, but three of its large moons, called Europa, Ganymede and Callisto, have warm underground oceans. How? Each moon is stretched and squeezed like a giant rubber ball by the other moons and Jupiter's huge gravity, heating them up and melting the ice. The same tidal heating gives Saturn's moon Enceladus a warm ocean, and maybe the moons of Uranus and Neptune have them too. If the biggest oceans in our solar system are way outside the Goldilocks Zone, hidden within the moons of the gas giants, maybe the same is true for other stars?

So which planets in our solar system are capable of supporting life? Earth of course. Mars maybe (it had a lot of water in the past). But what about Europa, or Enceladus? We could easily set the value of N_e at 4, and perhaps even then we are being over-cautious!

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

f1

A hydrothermal vent 1500m below sea level on the Juan de Fuca tectonic plate off the coast of Oregon. Credit: InVADER mission/ D. Kelley, University of Washington/NSF-OOI/WHOI.

Grand Prismatic Hot Spring, Yellowstone National Park, Wyoming. The colors are made by different bacterial communities that like living in extremely hot water. Credit: US Geological Survey.

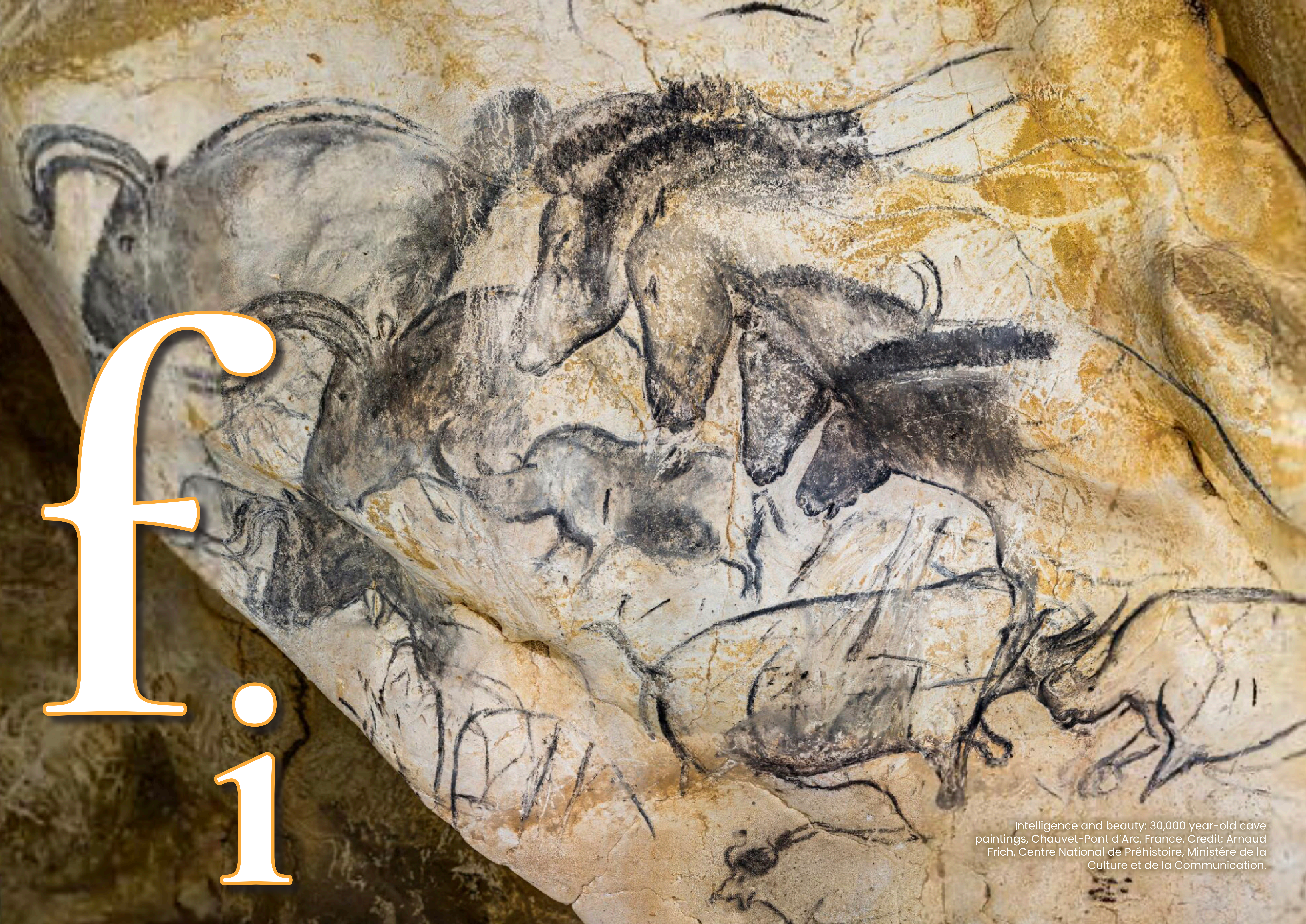
f_l The fraction of these planets where life actually emerges

The Earth is covered in life. From the deepest oceans to the highest mountains, dryest deserts to coldest ice sheets, life has found a way to thrive in almost every environment.

Life popped up almost as soon as the newborn Earth grew cool enough to have a solid crusty surface and pools of liquid water. What mix of conditions, or series of events, performed this primordial magic trick and turned chemistry into biology? Scientists have been pondering the question for centuries. One hypothesis suggests that life originated in hot, geothermal pools. These pools, like the ones still found in Yellowstone National Park and near active volcanoes around the world, have a mix of heat, sunlight, chemicals, and water. This combination could have provided the perfect conditions for complex organic molecules to form. Another theory points to hydrothermal vents on the ocean floor. These “black smokers” release hot water rich in minerals. While sunlight is absent, the Earth’s interior provides plenty of energy. Some scientists believe that these vents could have been a suitable environment for life to emerge.

Are these types of conditions unique to Earth? Not at all. Geothermal pools would have been commonplace on early Mars, and maybe early Venus. Hydrothermal vents are very likely bubbling through the ocean floors of Europa and Enceladus. Even if the process of making life is limited to how “we” were made, then the conditions to repeat the magic are truly universal. And if there are other ways currently known to science, then that only pushes the value of f_l up and up!

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$



fi

Intelligence and beauty: 30,000 year-old cave paintings, Chauvet-Pont d’Arc, France. Credit: Arnaud Frich, Centre National de Préhistoire, Ministére de la Culture et de la Communication.

f_i The fraction of these planets where intelligent life emerges

Humans are intelligent beings, most of the time. Intelligence evolved to help our ancestors to survive and thrive in the most extreme conditions across our planet, and beyond. Humans have created complex tools, built cities, and expressed their imagination in art. But are we truly alone in our intelligence?

If you look carefully, intelligence is everywhere. Whales and dolphins have large brains and communicate with each other in complex ways. Octopuses are known for their problem-solving skills and ability to learn. Ants and bees work together in organized societies, and crows have demonstrated impressive problem-solving abilities. Even plants show signs of intelligence. Trees can communicate with each other through their roots and share resources. This suggests that intelligence is a widespread trait, not just limited to humans.

If the diversity of intelligence is almost as broad as life itself, it raises high hopes for the intelligence term in the Drake Equation. However, it is important to remember that intelligence takes time to develop. For our planet, billions of years were needed for multicellular life to appear, and even longer for intelligent life to emerge. But if we open our minds to how we define intelligence, a low value of f_i seems unthinkable!

Humpback whale mother and calf. Credit: NOAA.

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

The Allen Telescope Array radio telescope at the Hat Creek
Radio Observatory in northern California.
Image Credit: Simon Steel/SETI Institute.

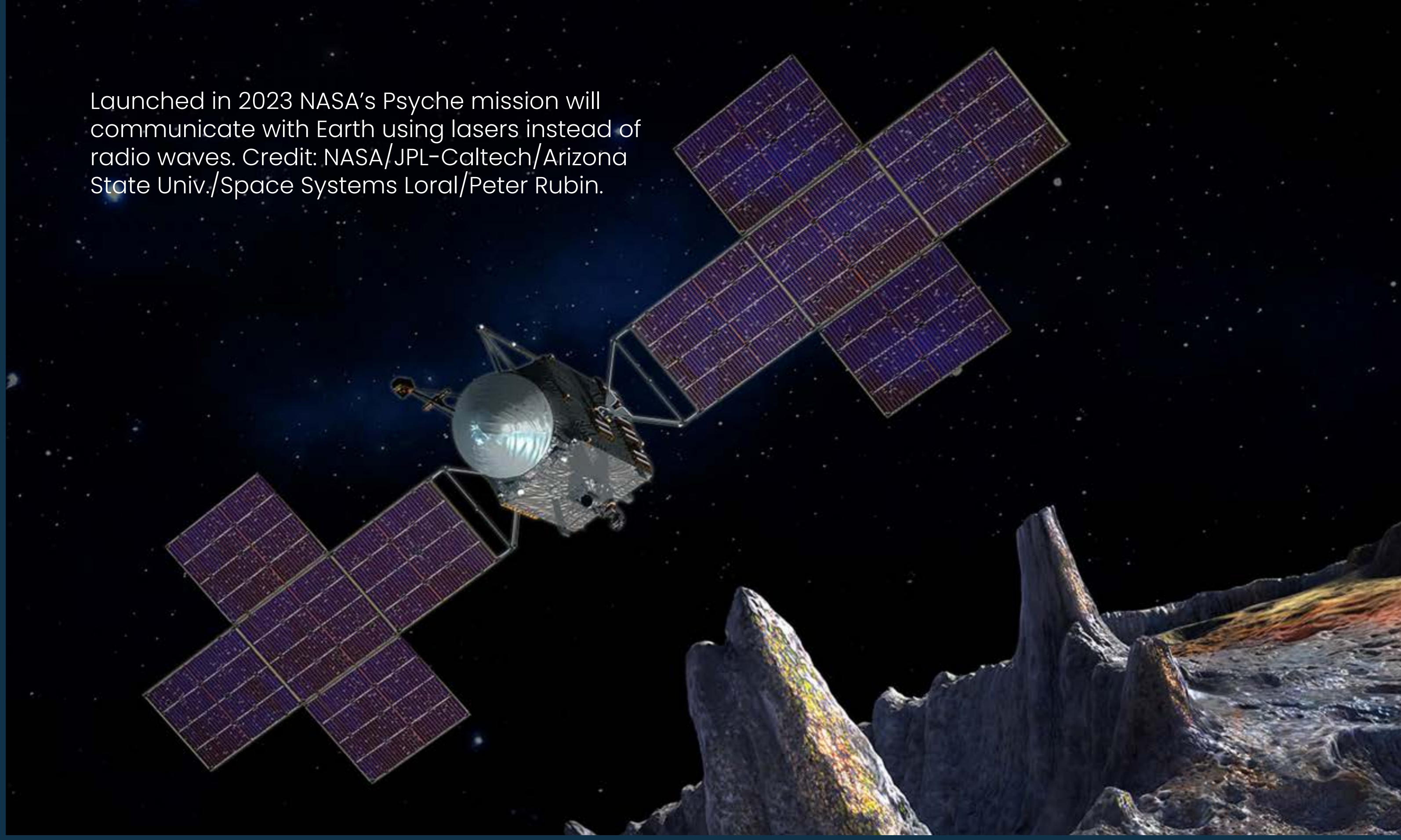
f_c The fraction of these planets where the intelligence can communicate across the stars

Humpback whales can communicate across entire oceans, but they have no ability, or maybe interest, in communicating between planets or star systems. Of all the intelligences on Earth, only humans have chosen to seek messages from the stars.

Radio transmissions are the message, or *technosignature*, of choice: radio waves are easy to generate and travel vast distances through the galaxy without being blocked by the gas and dust that fill space between the stars. With the radio telescopes we have today, we could detect a signal beamed to us from almost the far side of the Milky Way. That's billions of stars, billions of planets, within earshot of our radio telescopes.

There are other ways to eavesdrop on aliens. Radio "leakage" is something we humans contribute to space: radio communications, satellite and TV transmissions spill into space. If another nearby civilization did likewise, we could watch their TV shows too.
Radio SETI is still at the heart of the search, but optical SETI is fast becoming a new window to scan for technosignatures. Laser transmissions are a way to transmit a lot of information between planets or spaceships. Maybe a beam of light, and a message, might by chance point in our direction.

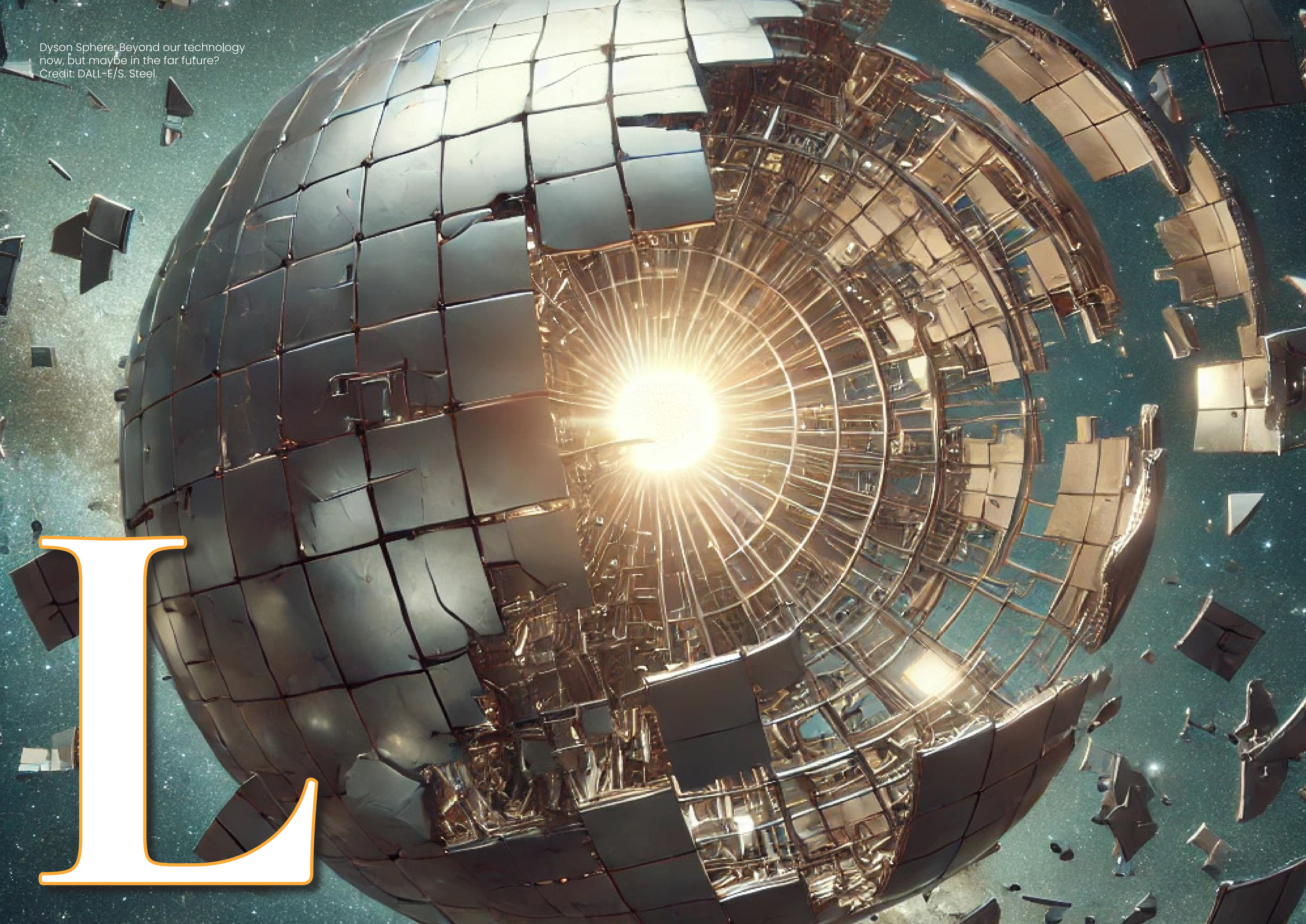
How can we even be sure that aliens use the same technology? One thing we definitely have in common is physics. Light in all its forms – radio, visible, X-ray - is a universal language that any scientist from any advanced civilization will understand. How a message is sent is not the problem. What the message says is a different matter altogether!



Launched in 2023 NASA's Psyche mission will communicate with Earth using lasers instead of radio waves. Credit: NASA/JPL-Caltech/Arizona State Univ./Space Systems Loral/Peter Rubin.

f_c remains as elusive now as when Frank Drake began making radio observations in 1960. But sixty years on, the technology has advanced beyond imagination, and with telescopes like the Allen Telescope Array, LaserSETI searching for optical laser flashes, and the COSMIC project using the Jansky Very Large Array, the most powerful radio telescope in the world, SETI has come of age. If the galaxy is filled with alien voices, we are finally ready to listen.

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$



Dyson Sphere: Beyond our technology now, but maybe in the far future? Credit: DALL-E/S. Steel.

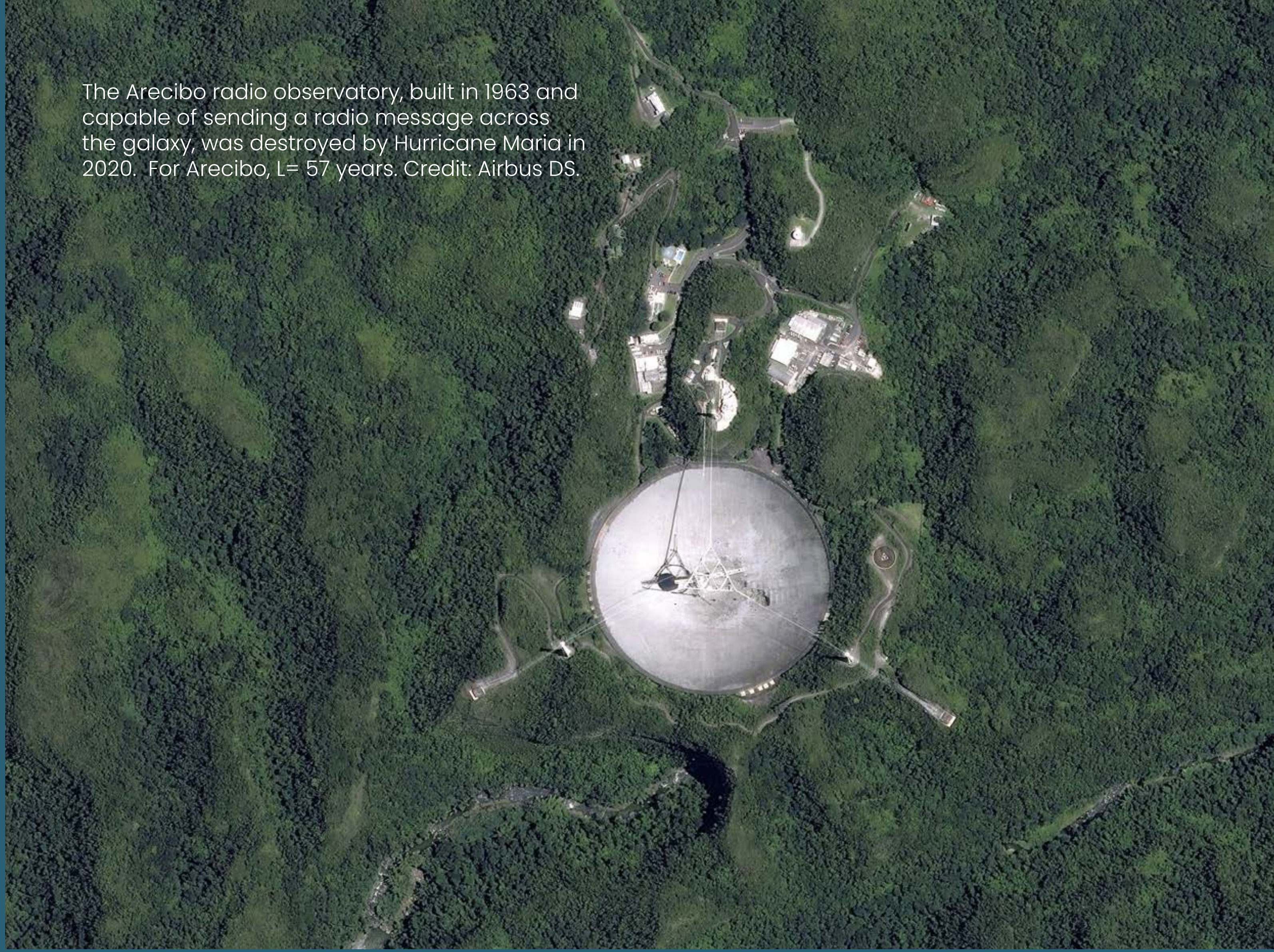
L

L The typical lifetime (in years) that a society can communicate

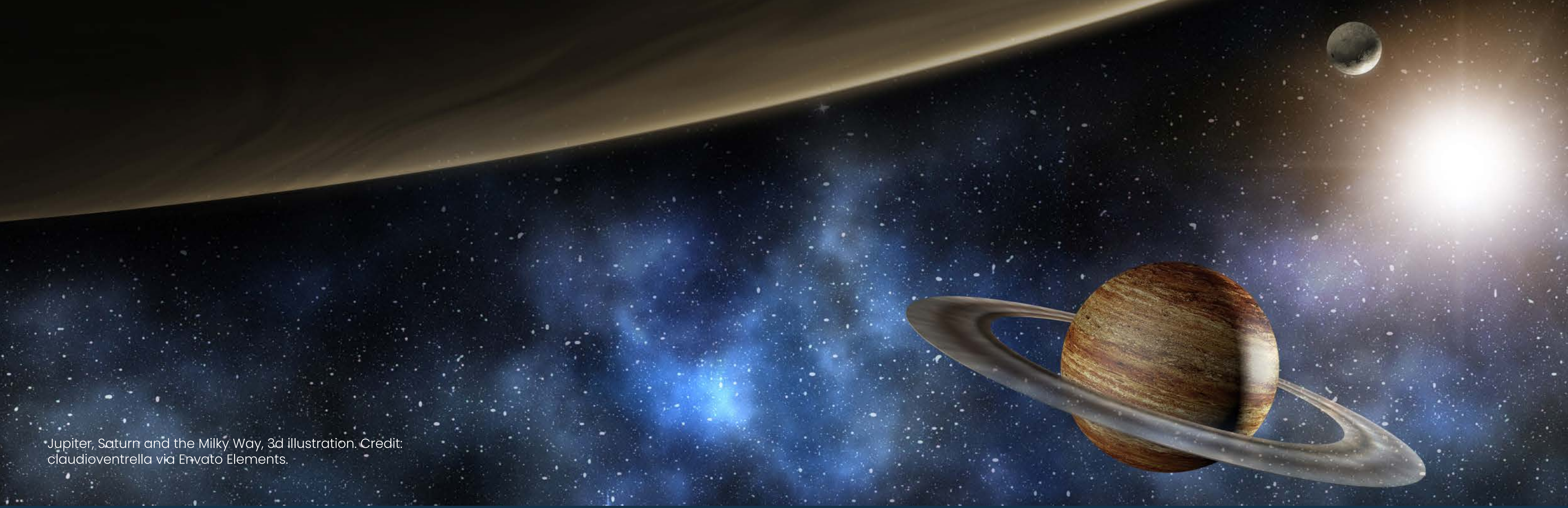
We have thought about life on other worlds for centuries, but the ability to send to or receive a message from the stars is only as old as radio astronomy. This means that for humanity, the value of “L” is just under 100 years. That’s not long, and a small number for L means a small number for N, and in a vast galaxy like the Milky Way, that means alien civilizations will be few and far between (and much more difficult to find). The longer a society remains able to communicate across the stars, the more alien civilizations are out there right now. Could we say the average lifetime is 1000 years, or a million years? Do advanced societies destroy themselves, or do they overcome war, pandemics and pollution to live to an amazing age? Using humans as a yardstick for “L” is probably a bad idea, but it does give us a chance to reflect on ourselves. Will we have a Star Trek future or Terminator future?

The length of time a civilization can communicate with us may also be limited by their success. Advanced societies will probably communicate in ways completely undetectable by our technology. Think trying to call a 1950s land line from a 5G smartphone. Maybe advanced aliens will make it simple for us, or maybe they’re not interested in such primitive neighbors!

If those advanced aliens decide not to invite us to the cosmic chat room, there are other ways to detect their existence, and one is by admiring their engineering skills. Highly advanced alien societies will need a lot of energy, and alien engineers could build a Dyson Sphere, a megastructure that surrounds an entire star to capture all its energy output. SETI Institute scientists are already looking for signs of nearby stars whose light is being blocked by Dyson Sphere construction. If any such artifact is discovered, it means societies can reach almost unbelievable levels of technology, and so have probably been around for a very long time. “L” can suddenly become a very big number!


The Arecibo radio observatory, built in 1963 and capable of sending a radio message across the galaxy, was destroyed by Hurricane Maria in 2020. For Arecibo, L= 57 years. Credit: Airbus DS.

$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$



Jupiter, Saturn and the Milky Way, 3d illustration. Credit: claudioventrella via Envato Elements.

Further reading

Introductory Level

Frank Drake and Dava Sobel,
Is Anyone Out There?
(Delacorte Press 1992)

Sarah Scholes,
Making Contact : Jill Tarter and the Search for Extraterrestrial Intelligence
(Pegasus Books 2017)

Nathalie Cabrol,
The Secret Life of the Universe: An Astrobiologist's Search for the Origins and Frontiers of Life (Scribner 2024)

More Advanced

Donald Goldsmith and Tobias Owen,
The Search for Life in the Universe 3rd Ed.
(Fox Chapel 2001)

Steven J. Dick,
The Biological Universe: The Twentieth Century Extraterrestrial Life Debate and the Limits of Science
(Cambridge University Press 1999)

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We are a nonprofit research organization.
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